RELATED APPLICATIONS

This application is a continuation-in-part application of U.S. Patent Application Serial No. 08/330,339, filed October 27, 1994.

FIELD OF THE INVENTION

The invention relates to illumination systems for video displays and more specifically to illumination systems for color projection video displays.

BACKGROUND OF THE INVENTION

Currently used techniques for color projection displays tend to be relatively inefficient in their light utilization. Such low efficiency limits the brightness of the display, which in effect limits the acceptable amount of ambient lighting in a viewing environment.

In certain presently used designs, light from a spectrally broad source is collected by a condensing lens and illuminates a spatial light modulator system. The spatial light modulator system comprises a two-dimensional array of pixels and the amount of light transmitted through each pixel is controlled electronically. A projection lens then images the array of pixels on a viewing screen, the magnification of the displayed image being determined by the particular characteristics of the projection lens. The light impinging on each

1   pixel of the spatial light modulator is spectrally broad (i.e. white

2   light).   Therefore, unless the system is modified to distinguish

3   colors, the display will be capable of only displaying black and white

4   images.

5   In many current systems used to modify such a system so that it

6   is capable of displaying color images each pixel of the spatial light

7   modulator is divided into three sub-pixels having equal areas. Each

8   of the three sub-pixels is covered with a micro-color filter having

9   a different spectral transmittance. For example, the filters are

10   chosen such that one filter transmits only red light, another filter

11   only green light, and the third filter only blue light.   The

12   transmittances of the three sub-pixels of each pixel of the spatial

13   light modulator can be controlled independently, resulting in the

14   ability to display a color image.

15   The inefficiency of the approach can be seen by considering the

16   following factors. The light illuminating a full pixel essentially

17   is white light and, consequently, the light impinging each sub-pixel

18   is also white light. The red filtered sub-pixel will transmit only

19   red light, absorbing all of the incident green and blue light.

20   Likewise,   the   other   two   sub-pixels   will   transmit   only   its

21   corresponding color, absorbing the other two colors. It is apparent

22   that this approach utilizes, at most, only one third of the available

23   light impinging on the modulator, and absorbs the rest.

24   Furthermore, state-of-the-art microcolor filters required to

25   produce acceptable color images are only approximately only 33%

26   efficient in transmitting the color that they are designed to

1   transmit. Therefore the overall light utilization of current color

2   projection displays is about 10%.

3   One approach for improving the efficiency of color projection

4   displays is found in U.S. Patent No. 5,161,042 issued on November 3,

5   1994 to H. Hamoda. In accordance therewith, the spectrally broad

6   input light is supplied to three dichroic mirrors which reflect three

7   different color components, e.g., red, green, and blue, in different

8   directions, i.e., at different angles with respect to each other. The

9   reflected components are then supplied to an array of lenses for

10   focusing the different color components so as to converge light beams

11   of similar wavelength ranges for transmission through a liquid crystal

12   display element so as to form combined color images on a display

13   screen. A further U.S. Patent No. 5,264,880, issued on

14   November 23, 1993, to R.A. Sprague et al., discloses a similar

15   approach to that of Hamoda wherein the dichroic mirrors are replaced

16   by a blaze grating for dispersing the color components of light

17   received thereat into a spectrum of different colors at different

18   angles relative to each other.

19   It is believed that, while such approaches can be used, the

20   losses of energy of each color component are sufficient to reduce the

21   efficiencies of such systems and to show the need for further

22   improvement in such display systems. Such improved display systems

23   would minimize such losses so as to provide for substantially the

24   total use of the received energy across the color spectrum in the

25   imaging display process resulting in an improvement of the efficiency

26   of the system.

1 <u>SUMMARY OF THE INVENTION</u>

2 The invention relates to a color projection display in which

3 received light, having a relatively broad spectrum, illuminates a

4 multi-level optical phase grating so as to disperse each of the color

5 components contained therein into a plurality of different diffraction

6 orders. In one embodiment, the diffraction orders of each color

7 component are then focussed onto a zero-order phase shift element

8 which phase shifts only the undiffracted light (i.e., the zero

9 diffraction order) with respect to the diffracted light (i.e., the

10 higher level diffraction orders). The output of the zero-order phase

11 shifter is then imaged onto a display having a plurality of pixels,

12 each pixel having sub-pixel regions assigned to transmit different

13 color components of light. The depths of the phase grating element

14 and the zero-order phase shifter are suitably selected so that they

15 are practical for manufacture and so that the area of chromaticity

16 space for the color components at the image plane is maximized.

17 The use of such a combination of multi-level phase grating and

18 a zero-order phase shifter, having suitably determined depths,

19 provides desired color components at each pixel in which essentially

20 little or no energy is lost. These color components are then suitably

21 combined to provide a color image at each of the pixels of the display

22 which is considerably brighter than that available using prior known

23 systems.

24 In another embodiment a broad spectrum light source illuminates

25 a multilevel optical phase element which disperses the broad spectrum

26 light from the light source by diffraction. A display having a number

27 of pixel elements, each capable of transmitting a predetermined

1   spectral region, is positioned within the near field region of the

2   multilevel optical phase element so as to receive the light dispersed

3   by the multilevel phase element. In one embodiment, the multilevel

4   phase element is periodic in two dimensions, thereby concentrating the

5   light in two dimensions.

6   In yet another embodiment, a method for displaying a color image

7   is disclosed. The method for displaying a color image includes

8   illuminating a multilevel optical phase element with a broad spectrum

9   light source. The multilevel phase element disperses light from the

10 light source by diffraction. A display having a plurality of pixel

11 elements, each transmitting a predetermined spectral region, is

12 positioned within the near field region of the multilevel optical

13 phase element to receive the dispersed light from the multilevel

14 optical phase element.

15 ## BRIEF DESCRIPTION OF THE DRAWINGS

16   This invention is pointed out with particularity in the appended

17 claims. The above and further advantages of this invention may be

18 better understood by referring to the following description taken in

19 conjunction with the accompanying drawing, in which:

20   Figs. 1 and 1A are block diagrams of an embodiment of a display

21 system using the technique of the invention;

22   Fig. 2   is a perspective diagram of an embodiment of the

23 multilevel optical phase element;

24   Fig. 2A is a perspective diagram of another embodiment of a

25 multilevel optical phase element of the invention;

1   Fig. 3 shows a graph of optimized phase grating depths of three

2   phase levels for a normalized pixel dimension for red, green and blue

3   color channels;

4   Fig. 4 shows the effective phase grating depths of three phase

5   levels for a normalized pixel dimension for the wavelengths of the

6   red, green and blue color components;

7   Fig. 5 shows the percent efficiencies of the spectral content for

8   the red, green and blue color components;

9   Fig. 6 shows the area of the chromaticity space covered when

10   using a particular embodiment of the invention on a standard 1976 CIE

11   chromaticity graph space;

12   Fig. 7 is a block diagram of another embodiment of a display

13   system of the invention;

14   Fig. 8 is a block diagram of yet another embodiment of a display

15   system of the invention; and

16   Figs. 9 and 9A are block diagrams of a multilevel phase element

17   and its complex conjugate, respectively.

18   DESCRIPTION OF THE PREFERRED EMBODIMENTS

19   In order to increase the light utilization of color displays, the

20   novel technique of the invention can be considered, in a conceptual

21   sense, as effectively concentrating all of the light of each color

22   component in a spectrally broad received light on to appropriate sub-

23   pixel regions at a color image plane, e.g., all of the incident red

24   light is concentrated in a manner such that it only illuminates the

25   sub-pixel regions corresponding to the red component thereof, all of

26   the incident green light is concentrated in a manner such that it only

1 illuminates the sub-pixel regions corresponding to the green component

2 thereof, and all of the incident blue light is concentrated in a

3 manner such that it only illuminates the sub-pixel regions

4 corresponding to the blue component thereof. By so doing, the use of

5 micro-filters is not necessary, and the theoretical light utilization

6 efficiency of such technique approaches 100%.

7 The invention achieves such light utilization based on a

8 technique referred to as aperture filling. Aperture filling is

9 described, for example, in the article, "Aperture filling of phase-

10 locked laser arrays" by G.J. Swanson et al., Optics Letters, Vol. 12,

11 April 1987. This article describes a method for increasing the energy

12 in the central lobe of a far-field pattern of a phase-locked laser

13 array. In accordance with the invention, the underlying physics of

14 this technique is modified and extended in a unique manner in order

15 to solve the color display problem of light utilization.

16 The basic physics behind aperture filling is herein described.

17 A binary amplitude grating (a grating having a transmittance of 1 or

18 0) with a fill factor (the ratio of the transmitting area to the total

19 area) of greater than or equal to 0.25, has, aside from a phase shift

20 of the zero order, a Fourier transform identical to that of a binary

21 phase grating having the same fill-factor as the binary amplitude

22 grating.

23 This statement implies that by placing a zero-order phase shift

24 element in the transform plane of an a focal imaging system, the light

25 from an aperture with a fill-factor of $\geq$ .25, can be uniformly spread

26 out of fill the entire aperture. Further, by invoking reciprocity,

1   light from a uniform aperture can be concentrated to produce an

2   underfilled aperture with a fill-factor of ≥ .25.

3   In making use of such concepts for improving the color projection

4   display efficiency, the above phenomenon can be modified to

5   substantially improve the light throughput thereof. A system

6   embodying the technique in accordance with the invention is shown in

7   Figs. 1 and 2, wherein a multi-level, e.g., a three-level, phase

8   grating is illuminated with a spectrally broad light from a source 10,

9   such as a tungsten halogen bulb or a xenon arc lamp. Alternatively,

10   the light source may comprise three separate color component sources.

11   For example, three light emitting diodes (LEDs) or three laser

12   sources, each emitting a separate color such as red, green, and blue

13   color components. For the purposes of the particular description of

14   a preferred embodiment of the invention, it is assumed that the

15   illuminating source 10, whether a single broad spectrum source or

16   separate color sources, primarily includes color components of the

17   three wavelength regions, e.g., red, green, and blue. The lateral

18   dimension of each phase level, in one embodiment, is assumed to be

19   equal to the lateral dimension of a sub-pixel region of the spatial

20   light modulator. For illustrative purposes only, Fig. 1A shows only

21   two greatly magnified grating periods, each having corresponding three

22   phase depth levels, occupying the entire aperture. It should be

23   understood that a large plurality of grating periods, each

24   corresponding to a pixel of the overall color image, would normally

25   occupy an aperture.

1   If it is assumed that a first phase depth level measured with

2   respect to a second phase depth level at each grating period of the

3   phase grating 11 is equal to an integral number of wavelengths of red

4   light plus one-third of such wavelength, i.e., (m+0.33) where m is an

5   integer, and the third phase depth level, again measured with respect

6   to the second phase depth level, is an integer multiple of the

7   wavelength of red light, the red light that is illuminating a three-

8   level phase grating will in effect encounter a binary phase grating

9   with a fill-factor of 33%, and a phase depth of 0.33 wavelengths. The

10   red light will be dispersed from the phase grating 11 into a zero

11   diffraction order and a plurality higher level positive and negative

12   diffraction orders which are focussed on a zero-order phase shifter

13   13 via lens 12. If the zero diffraction order (undiffracted) is then

14   phase shifted by about 0.33 wavelengths of red light by phase shifter

15   13, the red light exiting the system will be concentrated via a lens

16   14 so as to fill only 33% of the output imaging plane 15 (Fig. 1A).

17   The same methodology as applied above to the red light range can

18   also be applied to the green and blue light ranges. The second phase

19   depth level at each grating period equals zero wavelengths of green

20   light by definition, and the first and third phase depth levels equal

21   (n - 0.33) and n' - 0.33) wavelengths of green light, respectively,

22   where n and n' are integers. The green light illuminating the phase

23   grating 11 will also effectively encounter a binary phase grating with

24   a fill-factor of 33%, and a phase depth of 0.33 wavelengths. If the

25   zero diffraction order is also effectively shifted by about 0.33

26   wavelengths, the green light exiting the system will be concentrated

1 so as to fill the 33% of the output imaging plane that is adjacent to

2 the 33% of the output plane occupied by the red light (Fig. 1A).

3 For the blue light, the phase depth of level of each grating

4 period, again measured with respect to the second phase depth level,

5 equals (p'+.33) wavelengths of blue (where p' is an integer), and the

6 first phase depth level is an integer multiple of wavelengths of blue

7 light. The blue light illuminating the grating will also in effect

8 encounter a binary phase grating with a fill-factor of 33%, and a

9 phase depth of 0.33 wavelengths of blue light. If the zero

10 diffraction order is also effectively shifted by about 0.33

11 wavelengths, the blue light exiting the system will be concentrated

12 so as to fill the remaining 33% of the imaging plane not occupied by

13 the red light and the green light (Fig 2.).

14 The above conditions for three discrete wavelengths can in theory

15 be met to any level of accuracy. However, in practice, the accuracy

16 is limited by the physical depths of the grating levels that can be

17 practically manufactured. Furthermore, the system can be designed to

18 operate over the entire visible spectrum, rather than at only three

19 discrete wavelength regions.

20 The area of chromaticity space spanned by a particular embodiment

21 of the invention depends on the relative depths of the three phase

22 level regions of each grating period corresponding to each pixel, and

23 the depth of the zero-order phase shifter. Since the phase depths are

24 relative, and measured with respect to the second phase depth level,

25 the second phase depth level is zero by definition, thereby leaving

26 three variables: the depths of phase levels 1 and 3 with respect to

27 phase level 2, and the depth of the zero order phase shifter. These

1   three parameters in effect define the performance of the overall

2   system, with the measure of performance being defined as the area of

3   chromaticity space that is so covered. The three depth parameters are

4   most easily optimized by performing a "global search" process that

5   spans the range of practicable manufacturable depths.   The goal

6   thereof is to select relative depths which will maximize the area and

7   the location of the spanned chromaticity space. An approach to such

8   process is discussed below.

9   In considering the first phase level of the grating period, the

10 phase shifts (in waves) ϕ^1_R, ϕ^1_G, and ϕ^1_B of the red, green, and blue

11 light can be expressed as:
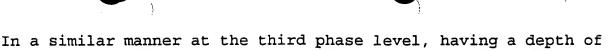
$$\Phi^1_R = \frac{d_1}{\lambda_R}(\eta - 1)$$

$$\Phi^1_G = \frac{d_1}{\lambda_G}(\eta - 1)$$

$$\Phi^1_B = \frac{d_1}{\lambda_B}(\eta - 1)$$

12 where η is the index of refraction of the phase grating, and d_1

13 is the depth of the first phase level with respect to the second phase

14 level. As mentioned above, it is desired that the phase shift $\phi^1_R =$

15 m+0.33, while the phase shift ϕ^1_G = n-0.33, and the ϕ^1_B = p, where m,

16 n , and p are all integers.

1   In a similar manner at the third phase level, having a depth of

2   d_3 with respect to the second phase level, the phase shifts are:

$$\Phi_R^3 = \frac{d_3}{\lambda_R}(\eta - 1)$$

$$\Phi_G^3 = \frac{d_3}{\lambda_G}(\eta - 1)$$

$$\Phi_B^3 = \frac{d_3}{\lambda_B}(\eta - 1)$$

3   Here, it is desired that the phase shift $\phi_R^3 = m'$, the phase shift ϕ_G^3

4    $= n' - 0.33$, and the phase shift $\phi_B^3 = p' + 0.33$ where m', n', and p' are

5   all integers.

6   Since the first and third phase levels of the grating are

7   referenced in depth to the second phase level of the grating, by

8   definition, $d_2 = 0$, and at the second phase level the phase shifts at

9   all three wavelengths is zero:

$$\Phi_R^2 = 0$$

$$\Phi_G^2 = 0$$

$$\Phi_B^2 = 0$$

1   In addition, at the zero-order phase shifter having a depth of

2   d_4, a phase shift of about one-third wavelength of each color is

3   required so that at the phase shifter:

$$\Phi_R^4 = \frac{d_4}{\lambda_R}(\eta - 1)$$

$$\Phi_G^4 = \frac{d_4}{\lambda_G}(\eta - 1)$$

$$\Phi_B^4 = \frac{d_4}{\lambda_B}(\eta - 1)$$

4   where $\phi_R^4 = r+0.33$, $\phi_G^4 = s+0.33$ and $\phi_B^4 = t+0.33$ (where r, s, and t are

5   integers).

6   Since the depths of d_1, d_2, d_3, and d_4 must be within practical

7   manufacturable limits, the following practical limitations can be

8   imposed thereon:

9       $-5\ \mu m \leq d_1 \leq +5\ \mu m$

10       $-5\ \mu m \leq d_3 \leq +5\ \mu m$

11       $-5\ \mu m \leq d_4 \leq +5\ \mu m$

12   and the value of η can be assumed at a conventional value, for

13   example, of 1.5.

14   Using the above equations, those in the art can then utilize a

15   well known global search algorithm technique, in which the values of

16   the depths d_1, d_3, and d_4 are changed in steps, Δd, of approximately

- 14 -

1   0.01 μm, and used to determine in each case the area of the

2   chromaticity space that can be spanned for each set of parameters.

3   The depths d_1, d_3, and d_4 for the solution providing a maximized area

4   can then be used as the practical physical depths for the three phase

5   level regions at each phase grating period and the practical physical

6   depth of the zero-order phase shifter 13.

7   In accordance with a specific embodiment of the invention, such

8   a process was used to determine the three optimum depth parameters for

9   a system operating with a uniform spectral source covering a 0.40-0.68

10 μm wavelength region, using both multilevel phase grating and zero-

11 order phase shift substrates assumed to have an index of refraction

12 of 1.5.   Exemplary results for optimized sub-pixel phase grating

13 depths of an exemplary pixel having a normalized pixel dimension are

14 shown in Fig. 3, with the red channel having a phase grating depth 16

15 of 1.84 μm relative to the green channel, and the blue channel having

16 a phase grating depth 17 of 4.0 μm relative to the green channel.

17   In order to illustrate how such an optimized phase grating design

18 conforms to the theory described above, the following three discrete

19 wavelengths can be considered: red=0.66 μm, green=0.54 μm, and

20 blue=0.46 μm.   The effective phase grating depths (modulo one-wave)

21 of the three sub-pixels at these three phase level regions are shown

22 in Fig. 4, where the solid line 18 represents red, the dashed line 19

23 represents green, and the dot-dash line 20 represents blue.   It should

24 be noted that in the first sub-pixel region, the phase grating depth

25 for red is approximates one-third wavelength of red light, and the

26 phase grating depths for green and blue are essentially zero.

27 Similarly, in the second sub-pixel region, the effective phase grating

1   depth for the green approximates one-third wavelength of green light,

2   and the phase grating depths for red and blue are approximately zero.

3   In the third sub-pixel region, the effective phase grating depth for

4   blue approximates one-third wavelength of blue light, while the phase

5   grating depths for red and green are approximately zero.

6   The optimized depth for the zero-order phase shifter 13 is 0.36

7   μm, which depth corresponds to 0.27 wavelengths of red, 0.33

8   wavelengths of green, and 0.39 wavelengths of blue. For this example,

9   it is noted that the optimum phase depth is less than one wave for all

10   three wavelengths. Fig. 2 is a perspective view of a multilevel phase

11   element which repeats periodically in the x-direction. Fig. 2A is a

12   perspective view of a multilevel phase element which repeats

13   periodically in both the x and y directions. Such a configuration

14   permits the incident light to be compressed both in the x-direction,

15   as in the prior embodiment, and also in the y-direction. Methods for

16   forming such multilevel phase elements are well known to those skilled

17   in the art. In particular a method for forming such multilevel

18   diffractive optical elements is disclosed in U.S. Patent 4,895,790 to

19   Swanson and Veldkamp, assigned to the common assignee of the present

20   invention and incorporated herein by reference.

21   The system's ability to concentrate the visible spectrum into

22   three color channels is illustrated in Fig. 5 for the above-mentioned

23   0.4-0.68 μm wavelength region. The solid curve 21 represents the %

24   efficiency of the spectral content of the red channel, the dashed

25   curve 22 represents the % efficiency of the spectral content of the

26   green channel, and the dash-dot curve 23 represents the % efficiency

27   of the spectral content of the blue channel. It should be noted that

1   the red channel efficiency peaks at the wavelength of 0.66 μm, the

2   green channel efficiency peaks at 0.54 μm, and the blue channel

3   efficiency peaks at 0.46 μm. The red channel has a secondary peak in

4   the far blue region of the spectrum. This blue light, in effect

5   "leaking" into the red channel, tends to limit the area covered in

6   chromaticity space. In some cases, it may be desired or required to

7   remove this unwanted blue light from the red channel by conventionally

8   filtering the red channel and such removal can be achieved with a

9   blue-blocking micro-filter, albeit at the cost of losing a minimal

10   amount of the blue light energy.

11   As is well known to the art, the spectral content of these three

12   color channels can then be used to determine the area of chromaticity

13   space spanned by the system. Fig. 6 shows a standard 1976 CIE

14   chromaticity space graph 25 which is well known to the art. The area

15   of the chromaticity space spanned by the embodiment discussed above

16   is depicted by three vertices of a triangle, defined by the plus

17   signs, in the graph. This area will be covered using essentially 100%

18   of the received source illumination.

19   Another embodiment of the invention does not require either the

20   zero-order phase plate 13 or the auxiliary optics 12, 14 of the

21   previous embodiment shown in Fig. 1. In this embodiment a broad

22   spectrum light source illuminates a multilevel optical phase element

23   which disperses the broad spectrum light from the light source into

24   diffraction orders. A modulation display, having a number of pixel

25   elements, each capable of transmitting a predetermined spectral

26   region, is positioned within the near field region of the multilevel

27   optical phase element so as to receive the light dispersed by the

1   multilevel phase element. In this embodiment, the free-space

2   propagation of light from the multilevel phase element produces a 1/3

3   wavelength phase shift of the undiffracted light with respect to the

4   diffracted light. Because of this, the phase plate 13 and auxiliary

5   optical elements 12, 14, which were required to produce the same zero-

6   order phase shift in the previous embodiment, are not required in this

7   embodiment.

8   To understand how free-space propagation provides the required

9   1/3 wavelength zero-order phase shift, assume that the amplitude

10 transmittance of the phase grating is expressed as:

$$t(x) = a_o + \sum_n a_n \exp\left[i2\pi \frac{n}{T}x\right]$$

11 where T is the grating period, a_0 is the amplitude of the

12 undiffracted light, the a_n's are the amplitude coefficients of the

13 various diffracted orders, and n is an indexing parameter.

14 If a unit amplitude plane wave illuminates this phase grating,

15 the light amplitude distribution, U_z, at a distance Z from the grating

16 plane is described by:

$$U_z(x) = a_o + \sum_n a_n \exp\left[i2\pi \frac{n}{T}x\right] \exp\left[-i\pi\lambda \frac{n^2}{T^2}Z\right].$$

17 where λ is the wavelength of the unit amplitude plane wave. The

18 irrelevant constants have been omitted from this equation. Thus the

19 free-space propagation over the distance Z has the effect of

20 introducing phase shifts to the diffracted components with respect to

21 the undiffracted component.

1   A distance, $Z_{1/3}$, is defined by the equation:

$$Z_{1/3} = \frac{2T^2}{3\lambda}$$

2   where λ is the central wavelength of the spectral distribution.

3   Substituting this equation for $Z_{1/3}$ into X in the previous

4   equation, results in the following light distribution:

$$U_{z_{1/3}}(x) = a_o + \sum_n a_n \exp\left[i2\pi\frac{n}{T}x\right]\exp\left[-i\frac{2}{3}\pi n^2\right]$$

5   The resulting phase shift (for all values of n that do not result

6   in an integer when divided by 3) is equal to an integer number of

7   wavelengths plus 1/3 wavelength. Since the integer number of waves

8   of phase shift are irrelevant, all of the values of n (that do not

9   result in an integer when divided by 3) effectively see a 1/3 wave

10 phase shift with respect to the undiffracted light. For values of n

11 that do result in an integer when divided by 3, the result is an

12 integer number of wavelengths of phase shift. However, for the

13 grating described above, the a_n's (for n divisible by 3) are zero.

14 Thus, the net result of free-space propagation over the distance

15 $Z_{1/3}$, is to produce a light distribution where the undiffracted light

16 is phase-shifted by 1/3 wavelength with respect to the diffracted

17 light. It is at this location that the modulation display, such as

18 a liquid crystal light modulator, is placed. With such a positioning,

19 no phase shift element 13 or additional optics 12, 14 are needed.

1   It should be noted that the propagation distance $Z_{1/3}$ is a

2   function of wavelength. Therefore, the free-space propagation just

3   discussed is strictly accurate at only one wavelength. However,

4   acceptable performance over the whole visible spectrum may be achieved

5   by choosing the $Z_{1/3}$ distance to correspond to the wavelength at the

6   center of the spectrum. That is, $Z_{1/3}$ should be chosen such that

$$\frac{2T^2}{3\lambda_{long}} < Z_{1/3} < \frac{2T^2}{3\lambda_{short}}$$

7   where λ_{long} is the longest wavelength of interest and λ_{short} is the

8   shortest wavelength of interest.

9   The above analysis assumes that the illumination source is a

10   point source at infinity, resulting in plane wave illumination. If

11   the illumination source is such that the approximation of a point

12   source at infinity which was just discussed is not valid, an

13   embodiment which describes a physically extended illumination source

14   must be considered.

15   In this embodiment, shown in Fig. 7, an illumination source 10'

16   has a dimension (for purposes of discussion referred to as the x-

17   dimension) of S_c. A condensing lens 30 having a focal length of F_c,

18   is positioned adjacent the illumination source 10', at a distance of

19   F_c. This configuration results in an angular source extent in the x-

20   dimension of $\theta_c \approx S_c/F_c$.

21   A figure of merit for performance is the ratio b/T, where b, the

22   blur, is the physical extent of the light pattern at the display

23   location in the x-dimension and T is the grating period. For good

1 performance, this ratio is less (typically much less) than 1/3. If

2 b is given by the expression b = $Z_{1/3}\theta_c$, the figure of merit becomes:

$$\frac{b}{T} = \frac{2T}{3\lambda_o}\theta_c$$

3 where λ_o is the center wavelength. For example, if an acceptable

4 figure of merit is 1/6, the center wavelength is .55 micrometers, and

5 the grating period is 48 micrometers, the resulting value for the

6 angular source size is θ_o = 2.9 milliradians. Thus, for a 50 mm focal

7 length condensing lens, a source with a size no larger than 145

8 micrometers in the x-dimension is required for this figure of merit

9 to hold. Hence, a source 10' with a physical dimension smaller than

10 most commercially available broad-spectrum incoherent sources should

11 be used to obtain good performance. Although broad spectrum

12 incoherent sources of the dimension just described are not generally

13 available, three spatially coherent monochromatic sources, such as 3

14 different wavelength LED's or laser diodes, could readily be used as

15 the illumination source 10'. As discussed with respect to the

16 previous example, the modulation display should be placed at a

17 distance $Z_{1/3}$ from the multilevel phase element 11.

18   Referring to Fig. 8, an embodiment which increases the extended

19 source performance includes a lenslet array 40 (in one embodiment

20 cylindrical lenslets), placed between the condensing lens 30 and the

21 multilevel phase element 11. The focal length of each lenslet 42 is

22 F_m, and the distance between the lenslet array 40 and the multilevel

23 phase element 11 is Z_s + F_m. Thus, Z_s is the distance between the

24 imaged source 22 and the multilevel phase element 11. Each lenslet 42

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focusses an image 44 of the extended source, S_c, at a distance F_m from

the lenslet array 40. Each of these imaged sources 44 will be of

physical dimension, S_m, in the x-dimension, where $S_m = (F_m\ S_c)/F_c$

4   centered about the optical axis of the respective lenslet 42.

5   For an image 44 of dimension S_m that lies on the optical axis of

6   the condensing lens, a Fresnel diffraction calculation indicates that

7   the light amplitude distribution at a distance Z from the multilevel

8   phase element 11 is given by the expression:

$$U'_{z(x)} = \exp\left[i\frac{\pi}{\lambda}\frac{x^2}{Z+Z_s}\right]\left[a_o + \sum_n \exp\left[-i\pi\lambda\frac{n^2}{T^2}\frac{Z_s Z}{Z+Z_s}\right]\exp\left[-i2\pi\frac{n}{T}\frac{Z_s}{Z+Z_s}x\right]\right]$$

9   in which the irrelevant constant factors have been neglected.

10   The first exponential term in the series is the wavefront curvature

11   introduced by the lenslet 44. The first exponential term after the

12   summation sign represents the phase shifts incurred by the various

13   diffraction orders. Again, what is desired is for all of the phase

14   shifts for values of n which do not result in integers, when divided

15   by three, be equal to 1/3 wave. For this to be the case, Z must be

16   given by the expression:

$$Z = \frac{2T^2 Z_s}{3\lambda Z_s - 2T^2}$$

17   Hence, in a manner similar to the case without lenslets, the

18   value of Z should be chosen such that:

- 22 -

$$\frac{2T^2Z_s}{3\lambda_{long}Z_s-2T^2} < Z < \frac{2T^2Z_s}{3\lambda_{short}Z_s-2T^2}$$

1 wherein T is the periodicity of said multilevel optical phase

2 element, Z_s is equal to the distance between said multilevel optical

3 phase element and said lenslets minus the focal length of said

4 lenslets, λ_{long} is the longest wavelength of interest and λ_{short} is the

5 shortest wavelength of interest.

6 Comparing this relationship with the relationship previously

7 shown for $Z_{1/3}$ (the optimum distance for the plane wave illumination

8 case):

$$\frac{Z_{1/3}}{Z} = 1 - \frac{2T^2}{3\lambda Z_s}$$

9 As Z_s approaches infinity, the distance, Z, approaches $Z_{1/3}$, as is

10 expected. For finite source distance Z_s, the optimum Z distance is

11 greater than the plane wave distance $Z_{1/3}$.

12 The last exponential term indicates that the period of the light

13 distribution at the optimum Z distance is no longer equal to the

14 period of the original phase grating. In effect, free-space

15 propagation from a source 10' located a finite distance from the

16 grating 11 results in a magnification. This magnification, M, is

17 given by the equation:

$$\frac{1}{M} = 1 = \frac{Z}{Z_s}$$

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1 Note that for a finite source distance, Z_s, the magnification factor

2 is greater than one.

3   The angular source size of the extended source 10 as seen at the

4 grating 11, S_m/Z_s. This angular source size results in a new blur

5 dimension, b_n, given by the expression:

$$b_n = \frac{S_m}{Z_s} Z = \frac{2T^2}{3\lambda Z_s - 2T^2} S_m$$

6   Because of the magnification described above, the new period of

7 the image pattern is, T_n:

$$T_n = MT = \frac{3\lambda Z_s T}{3\lambda Z_s - 2T^2}$$

8   The resulting fractional blur of the image pattern can now be

9 described by the relationships:

$$\frac{b_n}{T_n} = \frac{2T}{3\lambda Z_s} S_m = \frac{2T}{3\lambda Z_s} \frac{F_m}{F_c} S_c$$

10   The fractional blur, with the lenslet array 40 in position, can

11 be directly related to the fractional blur, b/T, without the lenslet

12 array 40, according to the expression:

$$\frac{b_n}{T_n} = \frac{b}{T} \frac{F_m}{Z_s}$$

1   This relationship clearly shows that the blurring can be dramatically

2   reduced by the proper introduction of the lenslet array 40.   The

3   reduction factor of the blurring is the ratio F_m/Z_s.

4   So far, consideration has only been given to the one lenslet 43

5   centered on the optical axis (OA) of the condensing lens 30.

6   Additional lenslets placed adjacent to the original lenslet 43 behave

7   in a manner identical to that described above for the original lenslet

8   43.   However, because of a coherent interaction between the light

9   traversing different lenslets, an additional constraint is placed on

10   the allowable center-to-center spacings of the lenslets.   The minimum

11   center-to-center spacing distance of the lenslets, L, is given by the

12   expression:

$$L = pT\left(\frac{Z + Z_S}{Z}\right)$$

13   where p is a positive integer.

14   In another embodiment, the multilevel phase element 11' shown in

15   Fig. 9, and discussed above with respect to Fig. 3, includes a double

16   step having an aggregate height of 4.0 μm.   The first step is 1.84 μm

17   measured from the base of the phase element and the second step is

18   2.16 μm measured from the top of the first step to the top of the

19   phase element. A phase element constructed with these dimensions will

20   function as described above.

21   If instead of the phase element 11' shown, a complex conjugate

22   phase element 11'' as shown in Fig. 9A is constructed, the complex

23   conjugate phase element 11'' will perform equivalently to the phase

24   element 11'.   The reason for referring to phase element 11'' as a

1 complex conjugate phase element will become readily apparent if the

2 complex conjugate phase element 11'' is placed adjacent the phase

3 element 11' such that the steps are aligned. Light passing through

4 both phase elements will be unaffected, and thus, just as the

5 integration of a wavefunction by its complex conjugate equals one,

6 phase element 11'' acts as the complex conjugate to phase element 11,

7 thereby permitting the incident light to pass both elements through

8 unaffected.

9 Unlike the phase element 11', the complex conjugate phase

10 element 11'' $Z_{1/3}$ is defined by:

$$Z_{1/3} = \frac{T^2}{3\lambda}$$

11 wherein λ is the central wavelength of the spectral distribution.

12 To achieve acceptable performance over the whole visible spectrum

13 may be achieved by choosing the $Z_{1/3}$ distance to correspond to the

14 wavelength at the center of the spectrum.

$$\frac{T^2}{3\lambda_{long}} < Z_{1/3} < \frac{T^2}{3\lambda_{short}}$$

15 where λ_{long} is the longest wavelength of interest and λ_{short} is the

16 shortest wavelength of interest. Similarly, when lenslets are

17 employed in conjunction with the complex conjugate phase element 11'',

18 Z must be chosen such that:

$$\frac{T^2 Z_s}{3\lambda_{long}Z_s - T^2} < Z < \frac{T^2 Z_s}{3\lambda_{short}Z_s - T^2}$$

1   wherein T is the periodicity of said multilevel optical phase

2   element, Z_s is equal to the distance between said multilevel optical

3   phase element and said lenslets minus the focal length of said

4   lenslets, λ_{long} is the longest wavelength of interest and λ_{short} is the

5   shortest wavelength of interest. Thus, using a complex conjugate

6   phase element permits a closer spacing than is permitted by the non-

7   complex conjugate phase element.

8   Having shown the preferred embodiment, those skilled in the art

9   will realize many variations are possible which will still be within

10   the scope and spirit of the claimed invention. Therefore, it is the

11   intention to limit the invention only as indicated by the scope of the

12   following claims.